MOUNTAIN WAVES IN THE APPALACHIANS

CHARLES V. LINDSAY

U.S. Weather Bureau, Washington National Airport, Washington D.C.
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ABSTRACT

The mountain wave phenomenon in the Appalachian region, mainly through North Carolina, Virginia, West Virginia, Maryland, and Pennsylvania, is described. The important variables necessary for the formation of mountain waves are discussed and a typical wave pattern that occurred on January 19, 1960 is described. Radar observations, a new source of information on wave cloud patterns, will be described. Data for this study were collected primarily during the fall, winter, and spring of 1959–60.

1. INTRODUCTION

Many descriptions of the mountain wave phenomenon are available for mountain barriers throughout most of the world. However, study of the phenomenon in the vicinity of the Appalachians has been neglected and very few data on the phenomenon in this region have been collected. The purpose of this paper is to describe mountain waves in the Appalachian region and to discuss their importance.

2. OBSERVED WAVES

One of the most striking and spectacular cloud formations ever photographed over the Washington area is pictured in figure 1. These clouds persisted from about 1100 EST to 1500 EST on November 30, 1959. There were several pilot reports of turbulence and downdrafts over the general area of the clouds during this period. The base of the clouds was estimated as between 10,000 and 12,000 ft., m.s.l. The orientation of the long bands was from an azimuth of 230° extending toward 50°. The long cloud bands were estimated by pilots to be spaced between 4 and 5 miles apart, and were reported to extend all the way back to the mountains to the west of Washington. At least nine separate cloud bands can be counted in the photograph. These clouds were nearly stationary except for a slight drift of the entire cloud system downwind. Details of this particular case were previously reported by Colson and Lindsay [1].

During the period covered by the present study all obtainable pilot reports of mountain waves in the region of the Appalachians were collected and summarized in relation to meteorological variables. Those variables that seem to be most pertinent were the observed lenticular clouds, the position of the jet stream, and the 850-mb. flow.

Each of the 51 cases of mountain waves included in this study occurred after a cold outbreak of air. The frequency distribution of these waves according to observed altitude is shown in figure 2. During the three periods, January 3–19, February 20–March 5, and April 6–18, fresh outbreaks occurred with a remarkable frequency of every 3–4 days. The greatest number of reports of waves during a day was 7 on January 19 and the greatest number of days on which waves were observed during a month was 8 in April. Nearly all of the cases occurred between 0800 and 2000 EST; 86 percent occurred between 0900 and 1800 EST, and 63 percent of all cases occurred between 1000 and 1500 EST.

Figure 3 shows the places, through and to the lee of the Appalachian region, where waves were observed.

Figure 1.—The series of wave clouds over the Washington, D.C., area on November 30, 1959. Photograph is a composite of a series of photographs taken by E. Orr, U.S. Weather Bureau, from the roof of the Weather Bureau building at 24th and M Streets NW., in Washington. The view is from the west through north to east (left to right).

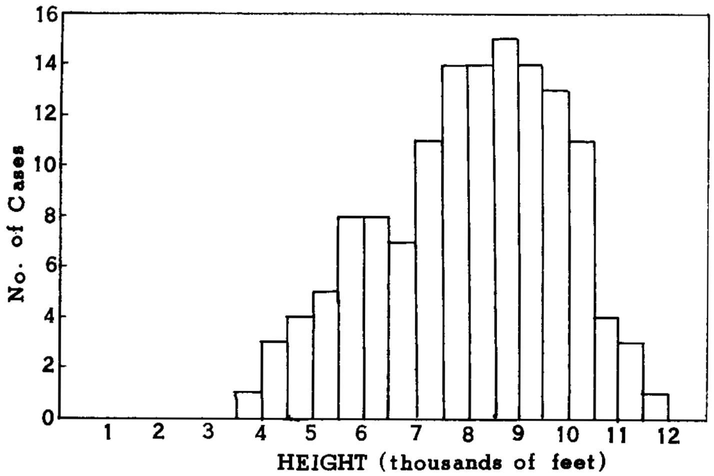

FIGURE 2.—Altitude and frequency of wave observations. (Period: fall, winter, and spring of 1959–60.)

Reports that could not be localized, because they were reported as occurring between two points on a flight, are indicated by lines connecting the two points and an arrow indicating the direction of flight. This distribution shown in figure 3 might be attributed in part to the location of the airways into Washington. Of the 51 pilot reports, 29 indicated downdrafts, 21 updrafts and downdrafts, and 1 an updraft alone. In eight of the cases vertical currents up to 1,000 to 2,000 ft./min. were reported.

On February 12, 1961, more recent than the period tabulated in this study, a wave occurrence was reported at 1719 EST 35 miles southeast of Roanoke, Va. The pilot reported updrafts and downdrafts of 2,000 to 3,000 ft./min. with abrupt stops at the top and bottom over a distance of 12 miles; the airspeed of his C195 airplane dropped from 150 to 90 kt. These vertical motions of 2,000 to 3,000 ft./min. are comparable with those found in the vicinity of mountain ranges in other parts of the world as described by Corby [2] and Kuettner [3]. Colson [4] found that vertical currents of 3,000 ft./min. or more have been observed in the Bishop, Calif. area of the Sierras with an extreme case of 8,000 ft./min. encountered by a pilot who feathered the propellers of his P–38 airplane and used it as a sailplane.

The height of the waves in all of the tabulated cases but one was observed to be above the general mountain top level. Although the characteristically smooth appearance of the orographic lenticular clouds indicates that exceptionally smooth flying conditions prevail as a rule in mountain waves, this is not always the case. Of the 51 cases examined, 8 indicated severe turbulence, 8 moderate turbulence, 2 light turbulence, and 1 smooth conditions; as 32 cases did not mention turbulence, it may be assumed that they also were smooth. By far the most common and most important area of severe turbulence in mountain waves is the area of the rotor clouds. These clouds form in the standing eddies under the wave crest at an altitude near the level of the height of the mountain which produces the wave. Turbulence has been experienced in rotor clouds that was more violent than any encountered in most thunderstorms.

The most dangerous situation for flying occurs when, although the turbulence is present, because of lack of moisture clouds do not form to mark it, or the sky is completely covered by a masking layer of low clouds; a plane may enter such an area of severe turbulence or downdrafts with no warning. Vertical accelerations two to five times the acceleration of gravity have been reported. Data obtained during the collection period indicate that when waves are observed or a significant number of lenticular clouds are observed throughout the area, the number of turbulence reports generally increases. During the days of waves, reports of clear air turbulence by pilots, usually below 10,000 ft., were frequent. Scorer [5] states that the most significant result that has come out of research on waves is that the greatest vertical velocities are usually in the first lee wave, and not over the top of the mountain producing the wave.

3. SYNOPTIC FEATURES

PRESENCE OF THE JET STREAM

The presence of a jet stream with its high wind speeds and strong vertical wind shear is an important factor in the occurrence of mountain waves. This has been pointed out in several studies made in the Rockies. All nine cases of strong waves over Denver, Colo., examined by Harrison [6] occurred when a jet stream was present with its axis either directly above the station or a short distance away. Colson [4] pointed out that the presence of a jet stream in the higher levels is the most probable situation, providing the strong winds and wind shear necessary in the formation of mountain waves. In the present study 80 percent of the cases were within 200 miles of the jet. It was observed during the "Sierra Wave Project" that a jet stream which is too strong tends to break up the wave cloud (which runs parallel to the mountain range) into bands oriented normal to the mountain range (cloud streets). This may be one reason why in this study very few cases of waves were observed when the 850-mb. wind speed normal to the mountain exceeded 40 kt.

850-MB. WIND DIRECTION AND SPEED

The wind direction and speed at 850 mb. were tabulated using the value over the mountains upstream from the wave report or in the vicinity of the report. It was found that in all cases of observed waves the wind direction was between 270° and 320°, with 63 percent of the cases from 290°–310°. This predominant direction is perpendicular to the average orientation of the mountain range. The wind speed was between 30 and 40 kt. in about 65 percent of the cases. In none of the cases was the speed less than 20 kt. and in only five cases was it greater than 40 kt.

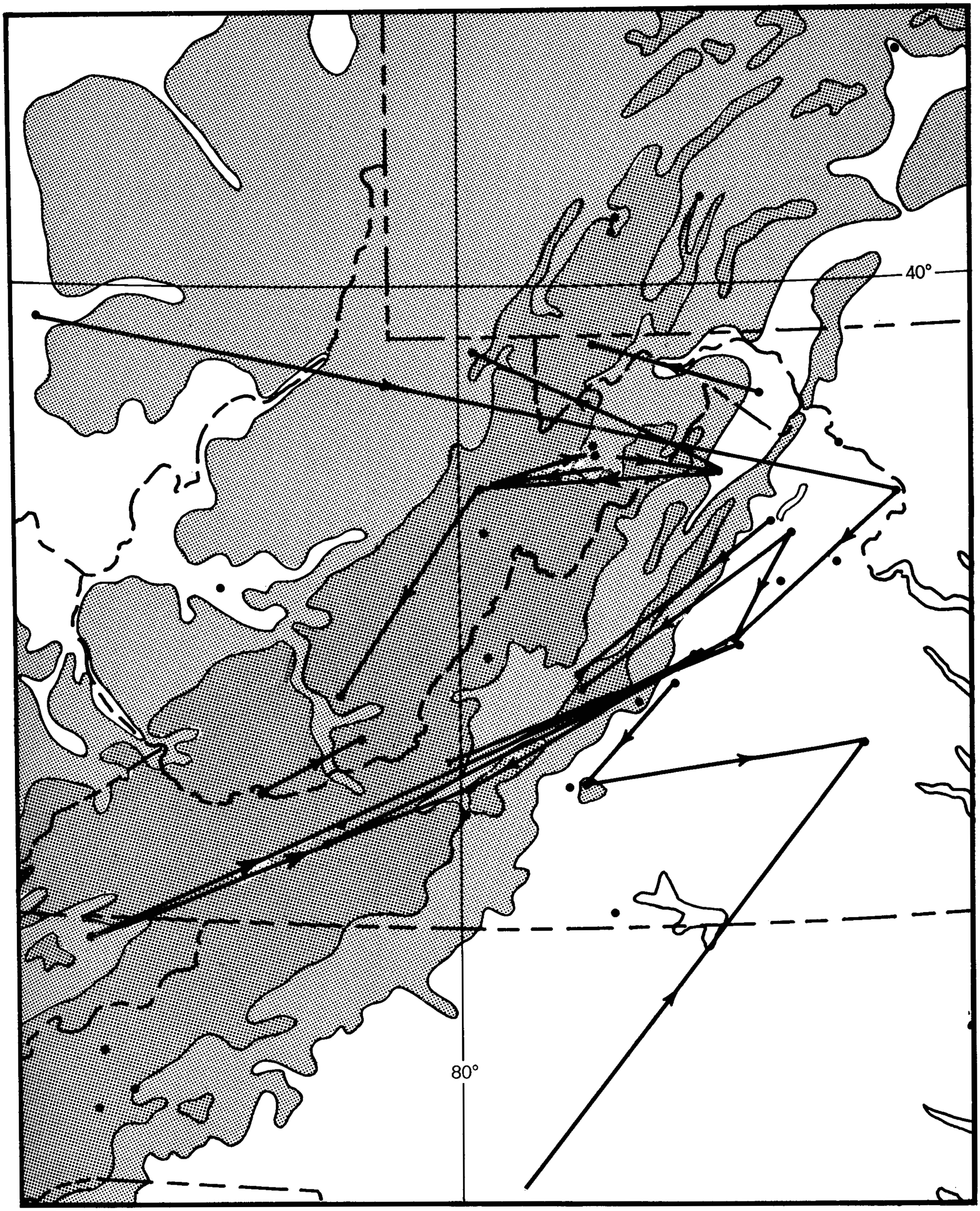

FIGURE 3.—Occurences of observed waves (Solid circles for specific reports and lines for occurences reported between two points, with arrow showing direction of flight). (Period: fall, winter, and spring of 1959–60.)

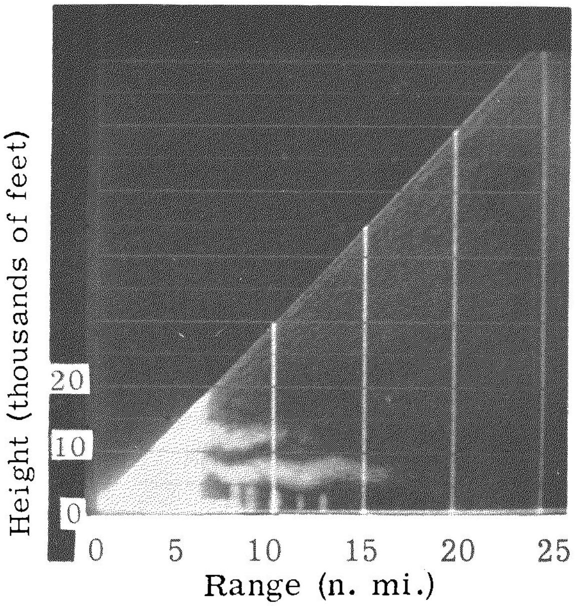

FIGURE 4.—Radarscope presentation of wave cloud, 1445 EST, November 6, 1960, at Washington National Airport, Washington, D.C.

4. RADAR ECHOES OF MOUNTAIN WAVES

The most recent development in the observation of the mountain wave is the use of radar. The details of an observation of a wave cloud pattern on the range-height-indicator (RHI) of the WSR–57 radar at Washington National Airport at 1330 EST, February 15, 1960 have been previously published [7]. A photograph of the RHI scope showed eight to possibly eleven wave echoes spaced about 3½ mi. apart. In the wave pattern pictured in figure 1, pilots observed the wavelength to be between 4 and 5 mi.

More recently, on October 20, 1960 at 1330 and 1400 EST, several echoes were observed [8] on the WSR–3 radar at Albany, N.Y., with the elevation angle set at about 20°. The set of echoes noted was immediately above the hills near Grafton Observatory, 8 to 16 mi. east, and above the Helderbergs at a distance of 11 to 14 mi. to the southwest. The echoes persisted for a considerable time with no appreciable movement. Shortly after 1400 EST, through a break in the cloudiness, very pronounced lenticular clouds could be observed above the Helderbergs. The Chief Airport Meteorologist [8] at Albany concluded that there might be some relationship between the altocumulus clouds and the radar echoes. His conclusion was independent as he did not have information on the observation made at Washington on February 15, 1960.

On October 28, 1960 a second observation was made at Albany when a number of altocumulus lenticularis were noted to the southwest. The radar elevation was set again at 20°. Several moderate echoes were observed in the same general direction, for example 95° at 16 mi., 230° at 14 mi., and 232° at 11 mi. An observation with

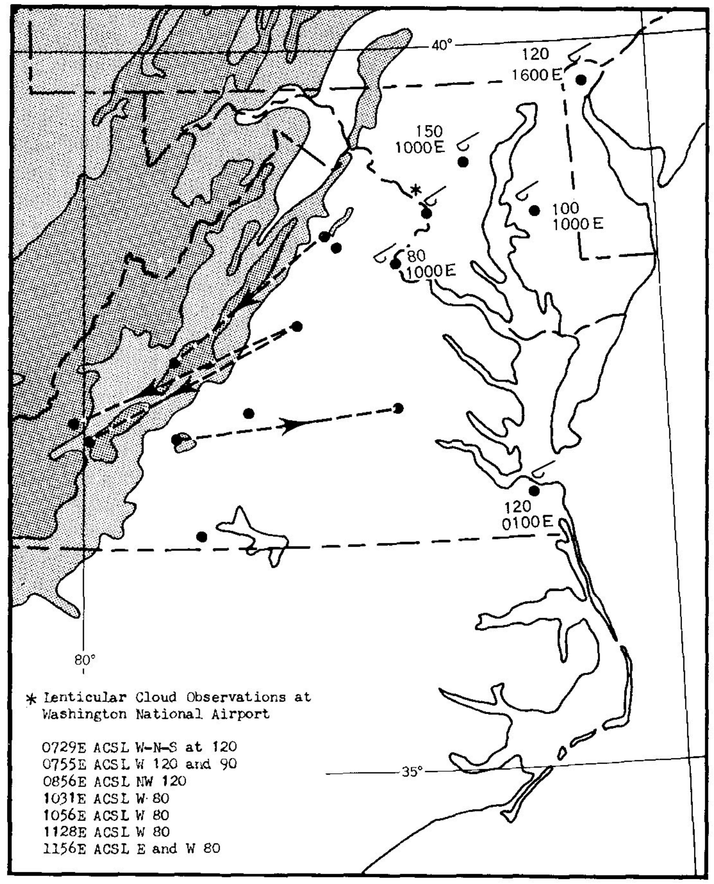

FIGURE 5.—Occurrences of observed waves (symbolized as in fig. 3) on January 19, 1960, showing also observations of lenticular clouds from Washington National Airport (detailed in inset) and from several other stations east of Washington. Azimuth and time of observation are plotted to left of cloud symbol.

the theodolite immediately east of the radar dome, with settings of 228° azimuth and 20° elevation, pointed directly to the center of the lenticular clouds to the southwest. The clouds to the east, if present, could not be seen because of lower clouds obscuring them.

On November 6, 1960 at 1445 EST a wave pattern was again observed on the WSR–57 at Washington National Airport. At this time at least eight wave clouds, oriented northeast-southwest, were visible from the airport. Both lenticular stratocumulus and lenticular altocumulus layers were observed with the wave of the latter over that of the other. Very little movement of the clouds was noted. Two layers were observed visually on the RHI scope and also on the TPQ–11 cloud detection radar in operation at the station. The bases and tops of the layers as indicated by the WSR–57 and the TPQ–11 seemed to agree and the bases of the upper layer were measured by the ceilometer to be at 9,000 ft. A picture of the RHI scope was taken with the antenna aimed at 299° on the 25-mi. range. The WSR–57 picture (fig. 4) shows a wave pattern and suggests the presence of two troughs and three crests. Three measurements from the picture gave a wavelength of about

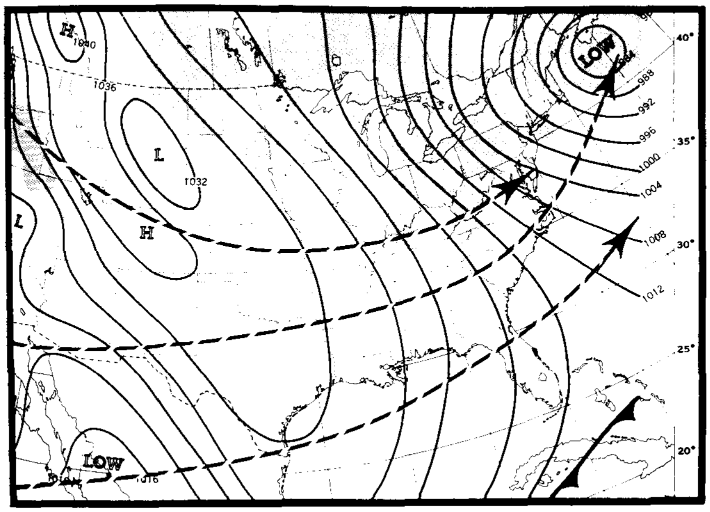

FIGURE 6.—Surface weather chart for 1300 EST, January 19, 1960, with jet streams shown by dashed arrows.

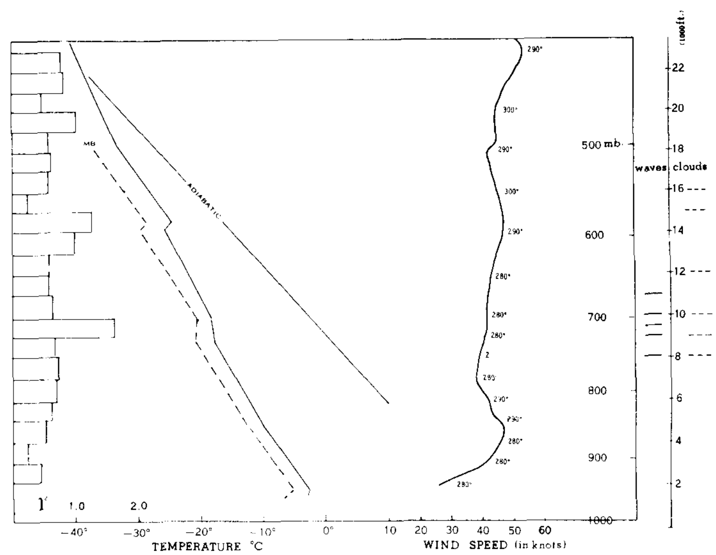

FIGURE 7.—Pittsburgh sounding, 0700 EST, January 19, 1960.

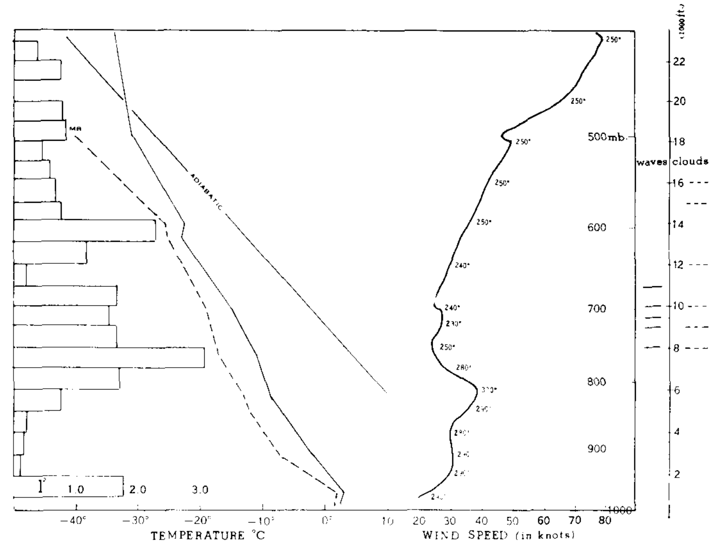

FIGURE 8.—Washington, D.C., sounding, 0700 EST, January 19, 1960.

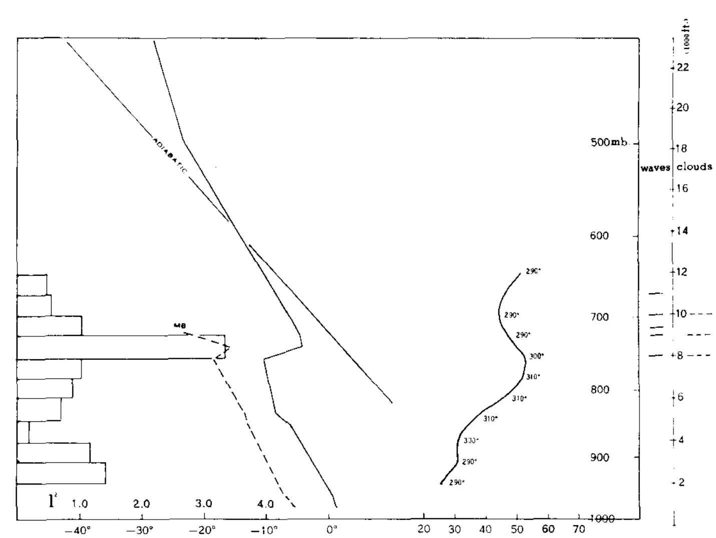

FIGURE 9.—Greensboro, N. C., sounding, 0700 EST, January 19, 1960.

4 mi. which is about the same wavelength observed previously on November 30, 1959 and on February 15, 1960 in the Washington area.

5. TYPICAL WAVE PATTERNS

On January 19, 1960, a typical synoptic pattern occurred for the development of waves. On this day between 0825 and 1420 EST seven reports of waves were made by pilots over Virginia to the lee of the mountains. These reports are plotted on figure 5. Three of the occurrences are shown by the solid circles and the other four occurred between the points indicated by the lines with the arrows showing the direction of flight. Also plotted are lenticular clouds that extended eastward to Delaware, eastern Maryland, and eastern Virginia. Similar cloud observations were made also in South Carolina and Georgia.

The surface weather chart (fig. 6) for 1300 EST of the 19th shows the post cold frontal pattern that is typical for the development of waves. Also shown is the presence of the jet stream over the immediate area which is important for the development of strong waves. During this period the wind direction and speed over the mountains were estimated from the 0700 EST 850-mb. chart to be about 310°, 33–40 kt.

Work by Scorer [5] shows the importance of the atmospheric stability in the establishment of waves. His stability term is given by $l^2=g\beta/U$ where U is the wind speed, β the static stability, and g the acceleration of gravity. According to Scorer l^2 should decrease with height if waves are at all possible. This condition is achieved either by a decrease of stability or an increase of wind speed with height. Analysis of numerous cases of waves by others has revealed that there is both a substantial increase in wind speed and a decrease of stability with height whenever waves are observed. Corby [2] has also done some verification of l^2. He has found that the decrease with height is usually substantial.

Theory indicates that the level of maximum amplitude must be near the level of maximum l^2. The maximum amplitude in general coincides with the layer of greatest stability. The more pronounced the stability, the closer to this layer the maximum amplitude tends to occur. Sometimes two or more wave systems may occur simultaneously at different levels. This happens when the vertical profile of l^2 shows more than one maximum. The wave systems associated with the different maxima will be different because of the difference in wind speed at their respective levels. In general, the upper wave will have a longer wavelength.

To apply the l^2 theory to the waves of January 19, 1960, the nearest upper air soundings for 0700 EST were analyzed. These soundings, for Pittsburgh, Washington, and Greensboro, are shown in figures 7, 8, and 9, where profiles of l^2 are plotted on the left side. The Pittsburgh sounding showed an average value of l^2 of 0.736 below 15,000 ft. and of 0.638 above that level. The Washington sounding showed 1.257 below 14,000 ft. and 0.646 above. Maxima of l^2 occurred at about 9,500 ft. and 14,500 ft. at Pittsburgh and at 7,500 and 13,500 ft. at Washington. The maximum l^2 of 8,500 ft. at Greensboro compares well with the reported height of the seven waves. The altitudes of the seven waves and the lenticular cloud heights observed at Washington and other stations within the area are indicated on the right side of the soundings. The fact that lenticular clouds were observed as low as 8,000 ft. and as high as 15,000 to 16,000 ft. would support the likelihood of waves at the second maximum l^2. Thus the plotting of the profiles of l^2 indicates both the likelihood and the height of waves.

6. CONCLUSIONS

Observations of mountain waves during the period covered by this study show that they can be rather widespread and particularly frequent during fall, winter, and early spring to the lee of the Appalachians. Additional observations of waves are being made at Washington National Airport to learn more of the nature of the problem in this region. Increased effort will also be made to obtain additional radar observations of waves and to learn more about why they can be detected at one time and not at another when they are known to be present.

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